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PREVENTION AND CONTROL OF AIR POLLUTION BY PROCESS CHANGES OR EQUIPMENT

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Cincinnati, Ohio

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*For presentation to the Expert Committee on Air Pollution, World Health Organization, Palais des Nations, on November 18, 1957 in Geneva, Switzerland

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I

PREVENTION AND CONTROL OF AIR POLLUTION BY PROCESS CHANGES OR EQUIPMENT

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and

Robert L. Stenburg

Discharge of airborne waste products normally associated with industrial activity is a new problem which is of growing concern in all industrial areas of the world. Atmospheric waste products may be classified in two broad categories, aerosols and gases.

Aerosols are liquid or solid particulates in suspension in a gaseous medium, usually air. In the field of air pollution these particulates are more specifically classified in terms of their method of generation, each class being further characterized by a particle size range. Dusts are solid particles formed by some disintegration process such as crushing, grinding or demolition. Normally dust particles range above 2 microns in diameter

but have been found to be as small as 0.1 micron. Fumes are solids generated by the condensation of vapors and may result from sublimation, distillation, or foundry processes, or from chemical reactions. The normal particle size of a fume is less than 1 micron. Fumes are often metals or metal oxides and their composition may differ materially from the substance from which they originated. Mists are liquid droplets smaller than 10 microns in diameter and are generated by condensation. Sprays are larger liquid droplets which are created by some mechanical disintegration process. In the collection of liquid or solid aerosols, chemical identity is not normally a factor in the choice of a control technique; however, in the control of gaseous emissions, chemical properties are often paramount in developing the technique employed.

The degree of source control necessary to overcome a specific area's air pollution problem is a function of the mass rate of emission of contaminants to the atmosphere within that area, the particular source concentrations present, the meteorological characteristics of the area, and the area's air pollution susceptibility.

Mass rates of emission and source concentration may be estimated or actual source samples may be taken. In order that correlations of mass rate of emission and source concentrations may be more applicable, source discharges should be expressed as a function of some unit of production, e.g., weight loss per unit of

throughput. Air pollution sources may be classified as domestic and industrial combustion processes, automotive engines, petroleum processing operations, chemical manufacturing processes, pyro- and electro- metallurgical processes, mineral processing, and food and feed manufacturing operations. The accompanying table gives the type of contaminant generally discharged to the atmosphere from typical sources in each of these broad classifications. It is important to recognize that while practically all such operations lead to the discharge of air pollutants, quantities within a single industrial category will vary as a result of production methods in use, raw materials employed, and air pollution control measures utilized.

The second factor, meteorological characteristics of the area, which must be evaluated in determining the degree of industrial source contaminant control necessary affects the rate of accumulation and dispersion of air contaminants for that specific area. The dispersion of area concentrations of atmospheric pollutants by air motion is a continuous process but the rate at which the contaminants are dispersed is variable and depends on the horizontal and vertical movements of the atmosphere.

TABLE 1 - SOURCES OF AIR POLLUTION

CLASS	AEROSOLS	GASES AND VAPORS	TYPICAL LOSS RATES
Combustion processes	Dust, fume	NO_2, SO_2, CO, organics, acids	0.05 - 1.5% by weight of fuel
Automotive engines	Fume	NO_2, CO, Acids, organics	4-7% by weight of fuel (Hydrocarbons)
Petroleum operations	Dust, mist	SO_2, H_2S, NH_3, CO, hydrocarbons, mercaptans	0.25 - 1.5% by weight of material processed
Chemical processes	Dust, mist, fume, spray	Process-dependent (SO_2, CO, NH_3, acids, organics, solvents, odors, sulfides)	0.5 - 2% by weight of material processed
Pyro- and electro-metallurgical processes	Dust, fume	SO_2, CO, fluorides, organics	0.5 - 2% by weight of material processed
Mineral processing	Dust, fume	Process-dependent (SO_2, CO, fluorides, organics)	1% - 3% by weight of material processed
Food and feed operations	Dust, mist	Odorous materials	0.25 - 1% by weight of material processed

Finally, consideration must be given to the area's air pollution susceptibility; that is, certain areas have a greater potential for air pollution than others. In this sense air pollution may be considered as an atmospheric condition defined in terms of its identifiable manifestations, i.e., irritation of the eyes and mucous membranes, reduced visibility, or plant, animal, or property damage.

Basically, four procedures are available for the control of effluent discharges to the atmosphere and thereby their detrimental effects. These are reduction of contaminant discharge at the source by application of control equipment, reduction at the source through raw material changes, operational changes or practices, or modification or replacement of process equipment, dilution of the source discharge by the use of tall stacks, and dispersion of source locations through allocation of land usage.

It is the purpose of this discussion to consider only the first two of these techniques.

THE APPLICATION OF CONTROL EQUIPMENT FOR THE PREVENTION OF AIR POLLUTION

The objectives sought for in the application of air pollution control equipment are the prevention of nuisance or physical damage to property, the elimination of health or safety

hazards to plant personnel and to the general populace, or the minimization of economic losses through the reduction of plant maintenance, the recovery of valuable waste products, or the improvement of product quality.

Performance of air pollution control equipment is assessed in terms of collection efficiencies. For particulate collection, efficiency may be defined as percent removal by weight, percent removal by weight per particle size range, or percent removal by count. Evaluation of equipment effectiveness may also be accomplished by the measurement of the relative blackness of the discharge or simply in terms of the amount of contaminant released. Gaseous control effectiveness is normally measured in terms of discharge concentrations of the contaminating material.

In discussing equipment used to control industrial air pollution at the source, it is convenient to divide it into two basic types, that for the control of solid and liquid aerosol emissions and that for the control of gaseous emissions.

Control of Aerosol Emissions

The general principles of dispersoid collection are applicable for both solid and liquid aerosols. While it is not the intent of this paper to review the fundamental theory behind these principles, sufficient theory will be presented to illustrate the removal mechanisms employed in each type of particulate collection equipment.

It is not uncommon for extremely wide ranges of particle size to be encountered in air pollution control work; also, concentrations of aerosols in industrial applications may range from a fraction of a grain per cubic foot to about 20 grains per cubic foot and occasionally loadings as high as several hundred grains per cubic foot are reached. It is evident, therefore, that with such extreme variations of aerosol size and concentration, many types of collection equipment will be required to solve the industrial effluent control problem.

When considering the removal of dispersoids from a carrier gas stream, the following factors affecting the choice of a particular piece of control equipment are significant:

Particulate characteristics, including particle size spectrum, effective particle shape, particle density, and physico-chemical properties such as stickiness, hygroscopic properties, agglomeration tendencies, corrosiveness, flowability, electrical conductivity, flammability, toxicity, etc.

Carrier gas characteristics, including temperature, pressure, and physical properties such as humidity, dew points of condensable components, density, viscosity, electrical conductivity, etc., and chemical properties such as corrosiveness, flammability, toxicity, etc.

Process factors, including constancy or variability of gas flow, volumetric gas rate, particulate concentration, collection efficiency requirements, allowable pressure drop, and product quality requirements.

Operational factors, including maintenance, continuity of operation, safety and health protection, and ultimate use of collected materials.

Constructional factors, including structural limitations such as floor space, headroom, etc., and material limitations such as pressure, temperature and corrosion service requirements, etc.

Gravity Settling Chambers

The gravity settling chamber is the simplest type of equipment employed for the collection of solid and liquid particulate discharges. It consists of a chamber in which the carrier gas velocity is reduced such as to allow the dispersoid to settle out of the moving stream under the action of gravity. The efficiency of collection for particles having a terminal settling velocity, μ_t, is expressed by the general equation:

$$E_g = \frac{u_t \ A_h}{Q} \quad \text{for } E_g \leq 1.0 \text{ (consistent units)} \qquad (1)$$

where, E_g = weight collection efficiency of gravity settling chamber for particles of terminal settling velocity, u_t, dimensionless.

u_t = particle terminal settling velocity, cm/sec or ft/sec

A_h = projected horizontal area of chamber, cm^2 or ft^2

Q = volumetric flow rate of carrier gas, cc/sec or ft^3/sec

From this equation it can be seen that, for a given volumetric gas flow rate, the collection efficiency for any particle having a settling velocity of u_t depends on the total plan cross section of the chamber and is independent of the height of the chamber. The minimum height of a gravity settling chamber, however, is established by the requirement that gas velocity through the chamber be sufficiently low as to prevent reentrainment of the separated dispersoid. Normally this velocity should not exceed 10 feet per second.

It is essential in this type of collector that the lateral velocity profile be as uniform as possible and that a low degree of turbulence relative to the settling velocity exist. Deviation from these requirements will result in reduced efficiency of collection. These criteria are normally achieved by employing gradual inlet transitions, guide vanes, or gas flow distribution plates.

Arrangements of vertical baffles have been used in some instances on the theory that increased efficiency will result

from the superimposition of inertial forces on the particles. However, inertial effects from such an arrangement are so small that they are exceeded by the effects of increased velocity through the collector and may even result in decreased efficiencies.

From a practical standpoint, industrial application of this equipment is limited. Practically, gravity separators are not employed for the removal of dispersoids below 40 microns in diameter because of the excessive size of the equipment which would result for collection below this size limit. Even for the particle size range above 40 microns, space requirements for this type of equipment are large.

A modification of the simple settling chamber employs a number of horizontal plates or trays within the chamber and this arrangement can lead to marked improvements in performance. As seen from Equation (1), collection efficiency depends directly upon projected horizontal area of the collector. Hence, the increase in efficiency obtained by the insertion of horizontal shelves is directly proportional to the number of shelves. Even with such equipment, however, the minimum particle size which can be collected in practice is about 10 microns. Use of this type of modified settling chamber is limited by difficulties in cleaning closely spaced trays and by their tendency to warp during high temperature operation. Also, this type collector is not practicable for handling dispersoid concentrations exceeding 1 grain per cubic foot.

Properly employed and designed gravity separators possess many inherent advantages: 1) low initial cost, 2) simple construction, 3) low pressure drop, 4) low maintenance requirements, 5) dry and continuous disposal of solid particulates, and 6) temperature and pressure limitations imposed only by materials of construction used. These advantages, however, are offset to a degree by several major disadvantages: 1) large space requirements, 2) decreasing collection efficiencies with decreasing particle size (very low efficiencies for particles below 10 to 40 microns in diameter), and 3) decreasing collection efficiencies with decreasing inlet dispersoid concentration.

Because of simplicity of construction and low maintenance costs, gravity settling chambers have found quite widespread application as pre-cleaners for higher efficiency collectors. This reduces the inlet dust loadings to the second-stage cleaner and can remove large, highly abrasive materials, thus reducing maintenance costs of high efficiency equipment which is more subject to abrasive deterioration. Settling chambers are used widely for the removal of large solid particulates from natural draft furnaces, kilns, etc.

Inertial Separators

This classification of control equipment includes all dry-type collectors which utilize the relatively greater inertia of the dispersoid to effect particulate-gas separation. Two types

of equipment utilize this fundamental principle: cyclonic separators, which produce continuous centrifugal force as a means of exerting the greater inertial effects of the dispersoid, and simple inertial or impaction separators, which employ incremental changes of direction of the carrier gas stream to exert the greater inertial effects of the dispersoid. Because of the importance of cyclonic separators in the air pollution control field, they will be discussed in a subsequent section.

An obstructing body present in a moving dispersoid-laden gas causes the gas stream to be deflected around the body. The dispersoid, however, as a result of its greater inertia, will tend to cross the fluid streamlines and to impinge on the surface of the obstructing body. Impingement separation may be analyzed theoretically in terms of so-called target efficiencies. Target efficiency is defined as the fraction of particles, in the fluid volume swept by an obstructing body, which will impinge on that body. Theoretical expressions for target efficiencies for simple geometries may be derived from classical hydrodynamics, but for more complex situations experimental determinations are required. It has been shown[1,2,3] that in the Stokes Law region, for any geometry, target efficiency should be some function of the dimensionless group, $[D_p^2 V_o(\rho_p - \rho)] \; / \; [18 D_B \mu]$

where, D_p = particle diameter, cm or ft

V_o = velocity of fluid relative to obstructing body, cm/sec or ft/sec

ρ_p = absolute density of particle, g/cc or lb/ft^3

ρ = density of fluid, g/cc or lb/ft^3

D_B = characteristic dimension of obstructing body, cm or ft

μ = viscosity of fluid, poise or lb mass/ft sec

For impingement of particles on an infinite cylinder or on a sphere, the following relationships hold theoretically:

$$E_t \text{ (cylinders)} = \frac{D_p^2 V_o (\rho_p - \rho)}{18 D_B \mu} \quad (\text{for } E_t \leq 1.0) \qquad (2)$$

$$E_t \text{ (sphere)} = \left[\frac{D_p^2 V_o (\rho_p - \rho)}{18 D_B \mu}\right]^2 \quad (\text{for } E_t \leq 1.0) \qquad (3)$$

where, E_t = target efficiency, dimensionless

It may, therefore, be said that collection efficiency of an impingement separator increases with increasing particle size, with relative gas velocity, and with particle density; and decreases as the size of the individual impingement surfaces increases and as viscosity of the carrier gas increases.

These relationships have been derived for conditions of streamline flow; they should, however, be approximately correct for turbulent flow. Further, these relationships were developed

for obstructing bodies in an infinite fluid and are applicable provided the adjacent collecting members are not so closely spaced as to cause appreciable distortion of the flow pattern; this condition is generally the case for commercial air filters and liquid scrubbers. Where the members are spaced such as to cause distortion of flow, the relationships for operating efficiencies will give conservative results.[4]

For the different types of equipment within this classification, the configuration of the obstructing bodies will vary from simple straight baffles to more complicated patterns which give maximum impaction efficiency with minimum pressure drop. The wide variation of impingement surface configuration employed in commercial units prohibits a detailed discussion of each. However, the more fundamental types, i.e., baffle type, orifice impaction type, high velocity gas reversal type, and louver type, will be discussed.

Perhaps the simplest type of impingement separator is the baffle chamber. Such a device forces the gas stream to follow a tortuous flow path which is obtained by the insertion of staggered plates or shaped obstacles into the gas stream. In such devices the gas is forced into a series of sudden changes of direction with resulting impaction of particles on solid surfaces. This equipment is capable of removing particles larger than 20 microns in diameter with pressure drops varying from 0.5 to 1.5 inches of water, depending upon the type of application and the configuration of the

impingement elements. Frequently commercial units are equipped with some mechanism for cleaning the impaction surfaces. Rappers are sometimes provided to remove the collected materials; other units employ a continuous or intermittent flowing films of water over the collecting surfaces.

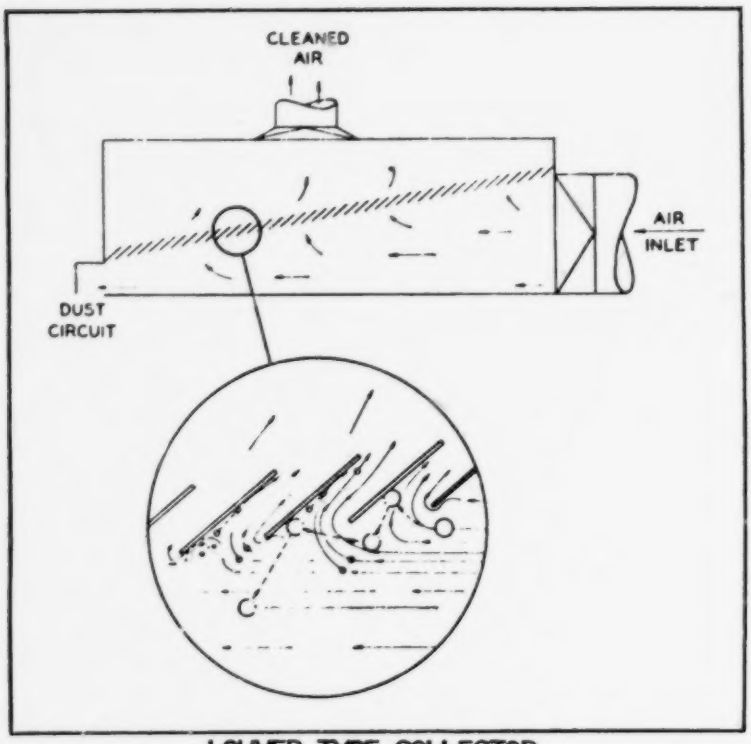
Because of the simplicity of construction, these units are capable of operating at elevated temperatures and pressures. However, care must be exercised that the materials to be separated are not "tacky" since build-up on the impingement element can change the efficiency characteristics of the unit. Also, due to the high impaction velocity in effect in this unit, abrasion is often critical.

Baffle type units have found wide application for solids removal in power plants and rotary kilns and for the removal of acid mists.

The second type of inertial separator is the orifice impaction type composed of two groups of orifice plates in series. The first group consists of orifice plates followed by impact plates whose apertures are staggered from those in the first plate. Passage of the gas stream through this assembly promotes agglomeration of the conveyed particulates. The second group consists of several plates with aligned orifices and acts as the collector element for the agglomerated particles. Many modifications of this type are available on the market but all employ the general principle of orifice impaction for the agglomeration and collection

of the dispersoid. High efficiencies have been obtained in this type unit for liquid aerosols larger than 2 microns in diameter. Normal velocities through the orifices are about 50-100 ft. per second and seldom exceed 150 ft. per second. The pressure drop through such units is approximately 2.0 to 2.5 orifice velocity heads.

The third class of inertial separators is the louver type. This unit contains a series of louvers or impingement elements set at an angle to the air stream such as to cause a single rapid reversal of air flow direction and thereby cause the dispersoids to impinge on the louvers. The particles thus impinged rebound back into the moving air stream in the inlet chamber and are removed from the collector by a secondary air circuit. Efficiency of this type unit is basically a function of the louver spacing, closer spacings producing higher efficiencies. Plugging due to build-up on the front and back sides of the louver or by mechanical obstructions will tend to reduce efficiency and volumetric capacity. For practical applications, efficiencies in this type unit are similar to those for other dry-type inertial collectors. Principle advantages of this type of collection equipment are simplicity and low cost of construction as well as moderately low pressure drop for the degree of removal obtained. Disadvantages are a tendency for accumulation of particles on the louvers with a corresponding reduction in efficiency and excessive abrasion of the louver elements,



LOUVER TYPE COLLECTOR

as well as an inability to handle tacky materials. Temperature and pressure limitations are again imposed only by the materials of construction.

In contrast to the above types of separators, the high velocity gas reversal chamber employs inertial separation, without impaction, for the removal of particulate matter. Here the bulk gas stream is caused to change direction at high velocities, thereby projecting particulate matter into an appropriately provided dead air space, from which the dispersoid is removed by gravity. Efficiencies for this type unit are low for particle sizes less than 50 microns. This type of installation is sometimes used as a pre-cleaner for more efficient control mechanisms to reduce the load of large diameter particles to these units.

Cyclonic Separators

The cyclone separator represents one of the least expensive and most important types of dispersoid collectors. It commonly consists of a cylindrical or conical chamber with provisions for the entry of the dispersoid-laden gases tangentially at one or more points, and for discharge through a central cylindrical opening at the top. The gas path generally follows a double vortex with the gas spiraling downward at the outside periphery of the body and upward through the outlet cylindrical section. Due to the rapid spiraling movement of the gas, the dispersoids are projected to the wall by centrifugal force and they then drop by gravity to the bottom of the body where they are removed. During cyclonic separation carrier gas rotational velocity may exceed by several times the average inlet gas velocity.

Based on analyses analogous to those for gravity separation, in which gravitational acceleration is replaced by centrifugal acceleration, a number of equations have been developed for the minimum diameter of particle which can theoretically be completely separated from the gas stream.[5] A typical equation illustrating the parameters involved is[6]

$$D_{p,min} = \sqrt{\frac{9\mu B}{\pi V N_t (\rho_p - \rho)}} \qquad (4)$$

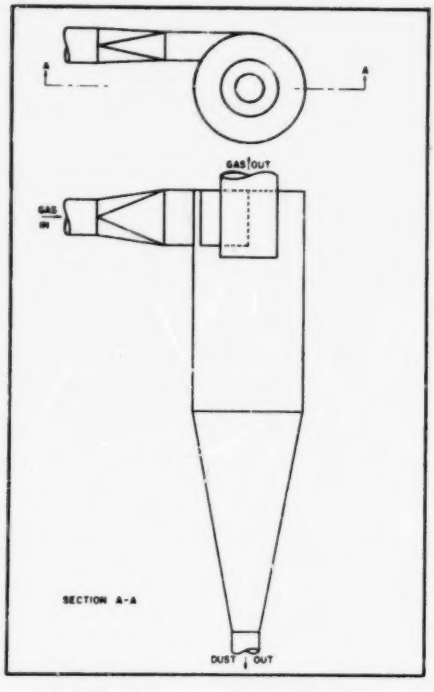


DIAGRAM OF A LONG, SLENDER SINGLE CYCLONE

where, $D_{p,min}$ = diameter of smallest particles completely collected, cm or ft

μ = viscosity of fluid, poise or lb mass/ft sec

B = width of cyclone inlet, cm or ft

V = average inlet velocity, cm/sec or ft/sec

N_t = number of turns made by gas stream in cyclone, dimensionless

ρ_p = absolute density of particles g/cc or lb/ft^3

ρ = density of fluid, g/cc or lb/ft^3

An extension of this analysis has been made leading to a method for the prediction of over-all cyclone efficiencies.[7] This simplified analysis assumes that the gas path within the cyclone is in the form of a rigid spiral and that the rotational

velocity equals average cyclone inlet velocity. In practice the flow pattern is considerably more complex leading to deviations from the efficiencies theoretically predicted.[8] Other studies have indicated that a "double eddy" at the inlet to the cyclone is superimposed on the double spiral and may in some instances affect dispersoid removal.[9,10,11,12]

The design factor having the greatest effect on collection efficiency is the cyclone diameter. For a given pressure drop, the smaller the diameter of the unit the higher the collection efficiency obtained, since centrifugal acceleration increases with decreasing radius of rotation. Centrifugal forces employed in modern designs vary from 5 to 2500 times gravity depending on the diameter of the cyclone. Present trends have been toward smaller diameter cyclones; however, with such units, in order to maintain adequate volumetric throughput, multiple units in parallel have been employed. For a given design, the effect of increasing gas throughput and, hence, increasing the inlet velocity, is normally to increase efficiency, but at the expense of increased pressure drop. For practical applications cyclone design must, therefore, be limited by pressure drops which are feasible with commercially available fans. This limitation usually dictates that inlet velocities be in the range from 20 to 70 ft. per second but equipment is normally designed for a velocity of 50 ft. per second. Normal present-day practice has established pressure drops for modern

cyclones from 1 to 20 inlet velocity heads depending upon the geometric proportions of the equipment and upon the collection efficiencies required.

Further efficiency increases are thought to result from an increase in cyclone body length but there are no conclusive experimental data to verify this. It has also been proposed[13] that a decrease in the diameter of the gas outlet produces a more significant effect on increase in efficiency. No general agreement has been reached as to the use of baffles, guide vanes, etc. for increasing cyclone efficiency.[14,15,16] The predominant opinion is that, in general, they reduce efficiency.

Design results for cyclonic separators are no better than particle-size-distribution data available to the designer and less than rigorous attention to these data often results in unsatisfactory operation. Although there is considerable information in the literature on particle size analysis, it has been noted that in practice data have sometimes been used which are statistically misleading and which have little physical significance when applied to cyclonic separator design. The measurement of particle size is not generally an absolute process and the method of measurement should, therefore, be based on the physical characteristics about which the information is desired. If, as in the case of cyclonic separator design, the size information desired is concerned with hydrodynamic and aerodynamic properties, the method should take into account particle mass, aerodynamic drag, etc., i.e., terminal settling velocity.

As a consequence, elutriation or sedimentation methods will give the more useful results for the design of cyclonic separators.

In practice cyclonic separators may be designed to satisfactorily collect particles over wide ranges of size and concentration and over wide ranges of pressure and temperature. Cyclones have operated at temperatures as high as 1000°C. and at pressures reaching 500 atmospheres. Satisfactory separation efficiencies, when employing the high efficiency, small diameter cyclones, are commonly obtained for dispersoids of 5-10 microns diameter and greater. In applications where high dust concentrations, on the order of 100 grains per cubic foot and greater, are encountered, correspondingly high collection efficiencies for smaller particle sizes are obtained. In this regard it is significant that increased dust loadings will result in decreased pressure drop and increased collection efficiencies.[17,18]

Cyclone designs are developed covering a wide range in size, geometry, and method of gas entry. Either cylindrical or conical cyclone bodies are employed with the diameter varying from a few inches, in the long slender units with high efficiencies in the sub-sieve particle size range, to 15 to 20 feet in the short, large diameter units employed in the ultra-sieve particle size range. Gas entries may be involute or tangential or may employ guide vanes to impart helical motion to the gas stream.

A variation of the simple cyclone design consists of units in which the centrifugal forces are developed by a mechanically

driven rotating element. These units are so designed as to concentrate the dispersoid at the periphery of a scroll, housing the mechanical rotating element, where the dispersoid is removed through an annular slot or a skimmer. The chief advantage of the mechanical centrifugal separator lies in its compactness. Such units appear to have collection efficiencies on the same order of magnitude as the small diameter, high efficiency cyclonic separators. A limitation of this type unit, however, is a tendency of certain types of solids to build up on the rotating element, causing plugging of the unit or rotor unbalance.

Cyclonic separators have found widespread acceptance for the control of gas-borne dispersoids in such industrial areas as aggregate processing, cement manufacture, feed and grain processing, food and beverage processing, mineral processing, paper and textile industries, and woodworking industries.

Universal acceptance of this type collector has resulted from certain inherent advantages: 1) low initial cost, 2) relatively simple construction, 3) dry and continuous disposal of solid particulates, 4) low pressure drop, 5) relatively low maintenance requirements, and 6) excluding mechanical centrifugals, temperature and pressure limitations imposed only by materials of construction. The application of this type separator is restricted, however, by three major disadvantages: 1) low collection efficiencies for particles below 5-10 microns in diameter, 2) decreasing

collection efficiencies for decreasing dispersoid concentrations in the gas stream, and 3) equipment is subject to severe abrasive deterioration.

Filters

For the collection of extremely fine particulates where moderate conditions of temperature, humidity, and corrosion can be maintained, cloth filters have found wide application rating second only to cyclonic collectors in scope of application for industrial air pollution control. Fundamentally this type of collector is designed to remove solid dispersoids from the carrier gas by "filtration" of the gas through a porous medium. Two basic types of filters are presently employed; the first utilizes a fibrous medium as the collecting element, and the second utilizes the medium as the support for a layer of collected particles, relying upon this coat of the collected material to serve as the principal collecting element. The latter type is, by far, the more important for industrial application and normally utilizes a fabric for the supporting medium.

The most common type of fabric collector is the tubular type consisting of a structure in which cylindrical fabric bags are suspended vertically over a tube sheet with the open end of the bag attached to the tube sheet. The tube sheet, in turn, forms the upper side of a gas entrance plenum which also serves as a dust collecting hopper. The particle-laden gases pass into the

gas entrance plenum or expansion chamber. Impingement on a baffle plate and a reversal of gas direction cause the heavier particles to drop by gravity into the hopper. The carrier gas then flows upward into the tubes and thence outward through the fabric leaving the particulate matter on a "cake" on the inside of the bags. The filter bags are periodically cleaned by some combination of rapping, shaking, or vibration, or by reverse air flow, causing the filter cake to be loosened and to fall into the hopper below.

Many types of fabric filters are classified under the general category of "bag filter." Basically they differ only with respect to bag shape, type of housing, fan location, and method of cleaning the fabric.

Separation of the dispersoid from the carrier gas stream is not a simple filtration or sieving since the pores of the fabric employed in fabric filters are normally many times the size of the particles separated. The theory for removal of dispersoids by a fabric filter has not been fully developed. It is postulated that initial deposition of the dispersoid, prior to the formation of a pre-coat, takes place through interception and impingement of the particulates on the fabric fibers, and due to Browniar diffusion, electrostatic attraction, and gravity settling within the pores. Efficiencies during pre-coat formation are usually low but increase as the pre-coat is formed until a final efficiency of separation, usually well over 99%, is obtained. Once formed, this

pre-coat becomes part of the filtering medium and the significant filtration mechanism then becomes sieving. In industrial applications with dust loadings normally encountered, this pre-coat usually builds up in a matter of minutes, sometimes even seconds. As previously indicated, the theory, as yet, is not exact as to the importance of each mechanism in the over-all separation, but the particle size range over which each is considered to be effective is shown in the accompanying table.[19]

Filtration Mechanisms and Particle Size Range Over Which Each is Effective

Mechanism	Particle Size Range (Microns)
Brownian diffusion	< 0.01 - 0.2
Interruption	> 1
Impingement	> 2
Electrostatic deposition	> 0.01
Sieving	> Filter medium interstices

Recent developments in the application of fabric filters for dispersoid control have been notable. Not only is there continued research toward the understanding of the mechanisms of filtration, there is an increased scope of employment of this type of control equipment engendered by the development of a wide variety of filter media and by the utilization of gas cooling techniques in conjunction with the control systems.

Recognition of the factors having an adverse effect on dispersoid removal efficiency has resulted in improved design and application of fabric filters. Some of the more common design deficiencies are: 1) excessive filter ratios, 2) improper selection of filter media, and 3) lack of on-stream capacity during cleaning.

The term "filter ratio" is defined as the ratio of carrier gas volume to gross filter area, and is sometimes termed superficial face velocity. Excessive filter ratios have several deleterious effects on dispersoid removal efficiency. In practice, the employment of high filter ratios for fine particles such as metallurgical fume results in a rapid build-up of filter resistance. This, in turn, requires more frequent shaking of the bag and results in increased bag wear. Further, higher filter velocities, with corresponding increase in filter resistance, may reach levels inconsistent with reasonable power consumption. The effects of high filter velocity are amplified in the filtration of fine particles, but are much less pronounced in the filtration of fibrous dusts which tend to form porous rather than packed cakes. Effects similar to those produced by excessive filter velocities are produced by high dispersoid concentrations in the gas stream. Decreased filter ratios, therefore, are recommended for high concentrations of dispersoids.

In practice, filter ratios range from 1 to 6 cu. ft. per minute per sq. ft. of cloth area; filter ratios of 3 cu. ft.

per minute per sq. ft. of cloth area have been established as a common standard for normal dusts; however, the recommended ratio for fine dust and metallurgical fumes should not exceed 1/2 to 1 cubic foot per minute per sq. ft. of cloth area.

Filter resistances corresponding to these filter ratios normally lie between 2 and 6 in. of water but some instances of satisfactory operation have been recorded with pressure drops as high as 12 in. of water. Total filter resistance consists of 1) that imposed by the fabric itself, and 2) that imposed by the collected dust layer formed on the surface of the fabric. Since flow through the filtering medium under conditions encountered in application is in the region of streamline flow, this total pressure drop can be expressed as a sum of two resistances, each of which is proportional to the filter velocity and to the effective thickness of the fabric and cake respectively.

$$\Delta p = K_o V_s + K_1 V_s W \quad \text{(special units)} \qquad (5)$$

where,

Δp = Pressure drop, in. water

K_o = Coefficient of fabric resistance, in. water/(ft/min)

V_s = Filter ratio, $(ft^3/min)/(ft^2)$

K_1 = Coefficient of cake resistance, in. water/(lb dust/ft^2)(ft/min)

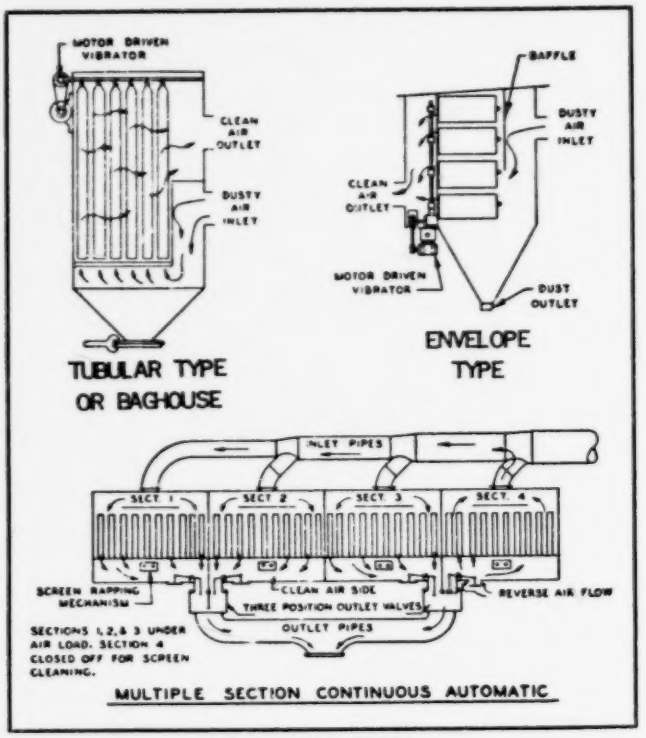
W = Weight of cake per unit cloth area, lb/ft^2

Improper application of filter media may result in unsatisfactory filter performance and in increased costs as a result of frequent bag replacement. In this regard, the fault normally lies in an inadequate appraisal of the operating limitations of the fabric. The more important of these limitations are temperature resistance, resistance to chemical attack, and abrasion resistance.

In the single compartment bag filter it is necessary that the gas flow to the unit be stopped during the cleaning or shaking cycle to allow the cake dislodged from the surface of the bag to fall by gravity to the hopper below. If requirements of the process being controlled are such that continuous operation is necessary, the bag filter must be of the multi-compartmented type to allow individual units of the bag filter to be successively off-stream during shaking. This is accomplished either manually in small units or by automatic programming control in large, fully automatic units. In this case sufficient cloth area must be provided to insure that filtering capacity will not be reduced during shaking periods when any one unit of the filter is off-stream. In this regard, it also should be noted that design should be based upon the maximum pressure drop anticipated since pressure drop does not remain constant throughout a filtration cycle but varies from a minimum to a maximum value as filtration progresses with corresponding fluctuations in volumetric throughput.

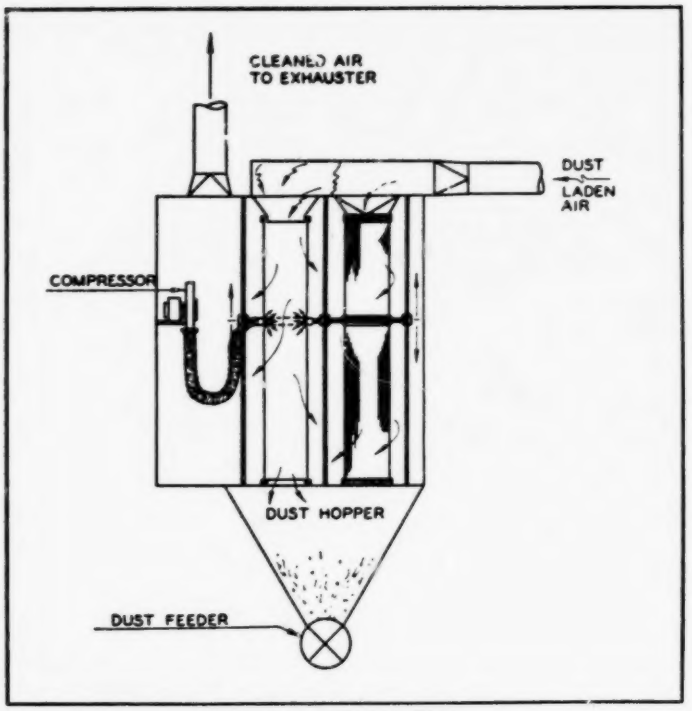
A modification of the simple tubular type fabric collector consists of a unit in which cloth envelopes supported on wire frames are employed in place of the tubular bags. In contrast with the bag filter, air is introduced on the outside of each envelope and passes through the fabric into the frame of the unit and thence out of the collector. The filter fabric on this type equipment is cleaned normally by a rapping action on the supporting frame. For very fine or tacky dispersoids this type of unit is not normally applicable since the efficiency of cleaning in such equipment is not as effective as that in the tubular type unit.

A comparatively recent innovation in the field of fabric filtration is the reverse jet filter. This unit differs basically from the tubular type unit as to the method of cleaning and as to the type filter medium employed. The tubular filters in this unit are cleaned by a high velocity air jet discharged from the inner side of a traversing annular ring which moves on the outside of the filter tube. The air jet passes through the fabric in a direction reverse to the normal flow and removes cake continuously from the filter surface. Current designs employ pressed felt tubes as the filtration medium. Three advantages are apparent in this type unit: 1) the unit requires no shut-downs or programming for cleaning, 2) it operates at filter ratios from 10 to 30 as opposed to the normal filter ratios of 1 to 6, and 3) the over-all filter resistance and, as a consequence, the volumetric throughput, can be maintained at a nearly constant value.



FABRIC FILTERS

Fabric collectors have several distinct advantages which enhance their employment. These are: 1) high collection efficiencies for all particle sizes, 2) relatively constant collection efficiencies for variable gas flow rates and dispersoid concentrations, 3) simple construction, 4) dry disposal of the collected material, and 5) nominal power consumption. The use of fabric as a filtering medium, however, imposes several disadvantages: 1) operating limitations are imposed by high carrier gas temperatures, high carrier gas humidity (gas temperatures must not fall below its dew point), and chemical activity of the gas or the dispersoid, 2) only solid particulates may be collected, 3) high maintenance and fabric replacement costs, and 4) large size of the equipment. The first of these limitations has been, in part,



REVERSE JET FILTER

overcome through the use of gas cooling apparatus where the problem of high gas temperature exists. In recent years the development of fabrics capable of withstanding higher temperatures has made the employment of gas cooling or conditioning more practical, since the degree of cooling required prior to their development often made gas conditioning economically unfeasible.

Three basic methods of lowering the temperature of gas streams have been employed: 1) cooling by radiation and convection, 2) cooling by evaporation, and 3) cooling by dilution with ambient air. The dilution method has not to date been used independently but rather as an adjunct to one of the first two methods. Radiation and convection cooling generally require a greater initial capital outlay than evaporative cooling, but operation is less costly.

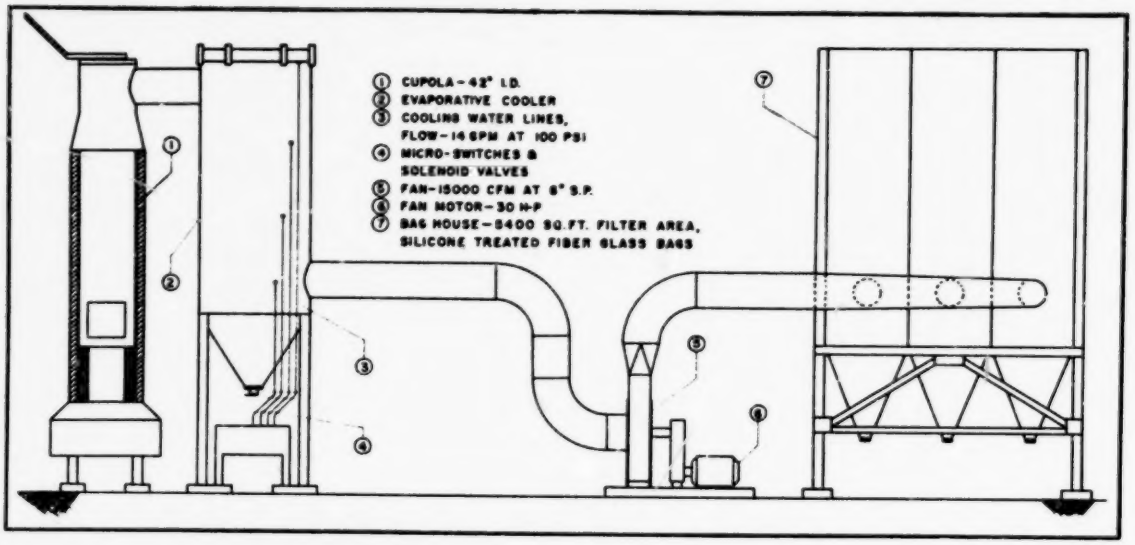

① CUPOLA - 42" I.D.
② EVAPORATIVE COOLER
③ COOLING WATER LINES, FLOW - 14 GPM AT 100 PSI
④ MICRO-SWITCHES & SOLENOID VALVES
⑤ FAN - 15000 CFM AT 8" S.P.
⑥ FAN MOTOR - 30 H-P
⑦ BAG HOUSE - 8400 SQ.FT. FILTER AREA, SILICONE TREATED FIBER GLASS BAGS

DIAGRAM OF AN EVAPORATIVE COOLER AND CLOTH FILTERING SYSTEM FOR A GRAY IRON CUPOLA

Evaporative coolers, however, necessitate the continuous use of cooling water with increased maintenance costs resulting from corrosion.

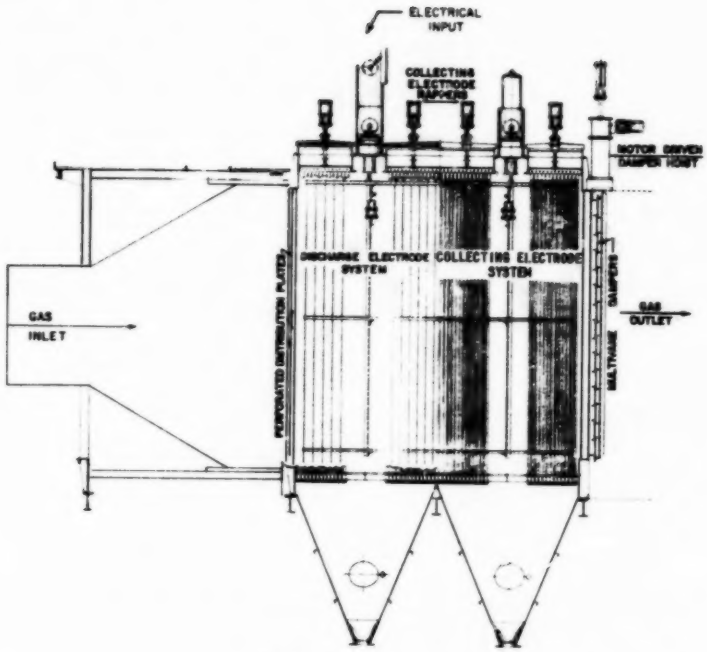
Electrical Precipitators

Industrial air pollution control applications requiring high collection efficiencies through wide ranges of particle size and having extreme operating conditions such that heavy duty control equipment is necessary have best been served by electrical precipitation.

Basically, electrical precipitation is accomplished by passing the dispersoid-laden carrier gas between two electrodes across which a unidirectional, high voltage potential is impressed.

One electrode, the discharge electrode, has a radius of curvature many times smaller than the second or collecting electrode. Due to the differential in radius of curvature and to the high voltage potential impressed across the electrodes, a corona discharge is established in the region of the discharge electrode and, as a result, a powerful ionizing field is formed. Potentials as high as 100,000 volts are used. As the dispersoids in the carrier gas pass through this field, they become charged and migrate, under the action of the powerful electrical field existing between the electrodes, to the oppositely charged collecting electrode. The particles, once deposited on the collecting electrode, lose their charge and are removed mechanically by rapping, vibration, or washing to a hopper below.

Electrical precipitation as employed in air pollution control work is generally carried out in a single-stage precipitator in which gas ionization and particulate collection are combined into a single step. There has been a very limited employment of a second type of precipitator, the two-stage unit, in which ionization is achieved in the first element of the equipment followed by collection in the second element. Variations in design in each type differ essentially only in the details by which the following fundamental functions are accomplished: 1) gas ionization resulting from corona discharge, 2) charging of the particles, 3) migration of the particles toward the collecting electrode, 4) deposition of the particles onto



ELECTRICAL PRECIPITATOR

the collecting electrode, and 5) removal of the collected material from the equipment.

There are two basic designs of the single-stage precipitator, the plate-type precipitator and the pipe-type precipitator. In the plate-type unit the collecting electrodes consist of parallel plates, either solid or of expanded metal, closely spaced rows of rods, chains, or wire, or specially formed shapes. In the pipe-type precipitator the collecting electrodes are formed by a nest of parallel tubes which may be square, round, or octagonal. In each case the discharge electrodes are wires or small, twisted rods which are suspended midway between the parallel collecting electrodes of the plate-type unit or axially along the length of the collecting electrodes in the pipe-type precipitator. Gas flow in the case of plate

precipitators may be either parallel or perpendicular to the discharge electrodes and, of course, parallel to the collecting electrodes, but in the case of the pipe-type precipitator it must be parallel to the discharge electrodes. The corona discharge in both types of precipitators is maintained throughout the length of the precipitator and it functions to provide ionization of the gas and to prevent redispersion of the precipitated dust by recharging neutral reentrained particles. The discharge electrodes usually are suspended vertically from an insulated support and are kept taut by a suspended weight at the bottom or by being stretched across an insulated frame.

Cleaning of the collecting electrodes for dry collection is accomplished by either periodic or continuous mechanical or electrical rapping to dislodge the collected material from the electrodes. In the film-cleaned precipitator, liquid is circulated over the collecting surfaces of the electrodes, and the material deposited is removed by washing. For liquid dispersoid collection the collected liquid is allowed to drain from the electrode surfaces under the action of gravity. It is common practice for the cleaning process to be carried out with the gas flow continuing and with the electrodes remaining energized, but this results in a tendency for reentrainment of the dust during the cleaning cycle with a consequent loss to the atmosphere. Specially formed collecting electrodes such as the hollow, pocket, or tulip types are used to reduce this tendency toward reentrainment during rapping. Collecting electrodes in the

plate-type unit generally are from 3 to 6 ft. wide and 10 to 18 ft. high, and in the pipe-type precipitator 6 to 15 ft. long. Discharge electrode to collecting electrode spacing in both types usually ranges from 3 to 8 in. Generally, the pipe-type precipitator is used for the removal of liquid dispersoids and the plate-type is employed for the collection of solid dispersoids.

In single-stage precipitators wherein particle charging and deposition take place simultaneously, the particles are not charged instantaneously; they assume a charge dependent upon electrostatic potential gradient, the dielectric constant, and the particle diameter.[20,21,22] Velocity of migration of a particle toward the collecting electrode is a function of the electrical force acting on the particle and the resistance to movement of that particle due to gas friction. However, practical migration velocities are in general greater than those calculated, because of the action of electric wind.[23] On this basis the following equation for collection efficiency has been derived.[24]

$$E_e = 1 - e^{-K_e \mu_e} \qquad (6)$$

where,

E_e = weight collection efficiency, dimensionless

K_e = electrical precipitation constant, sec/cm or sec/ft

μ_e = migration velocity, cm/sec or ft/sec

The electrical precipitation constant is a function of the precipitator geometry and the gas velocity through the precipitator. Theoretically this equation for collection efficiency is applicable only for a given size particle, and over-all efficiency must, therefore, be obtained by an integration procedure for a specific particle size distribution. In practice, however, particle migration velocity is generally determined experimentally for a class of particulates, employing a pilot-scale precipitator, and the average experimental velocity thus determined is then applied in design calculations in the above equation. Further, from the equation it is seen that efficiency varies logarithmically with the precipitation constant and migration velocity; hence, size of a precipitator increases exponentially with increase in required efficiency.

Although a complete discussion of electrical precipitation is beyond the scope of this paper, it should be noted that there are a number of important practical problems involved in the design and application of this equipment. Many of these problems result from an inability to predict the exact behavior of the particulate matter. In most cases this material is heterogeneous in size, shape, and physical properties.

Electrical resistivity of the particulates has such a great effect on efficiency that a small change will cause an appreciable difference in operating characteristics of the precipitator. High resistivity material, when deposited on the collecting electrode, will result not only in a reduction of potential across the

gas stream, but also in back ionization with a consequent reentrainment of the dust, both of which reduce efficiency.[25,26,27] Research on this subject has indicated that the critical resistivity value for deposited dust layers is about 2×10^{10} ohm centimeters.[28]

Several approaches have been used to resolve this problem and all are based upon lowering the effective resistivity of the deposited layer. Humidification, chemical gas conditioning, and temperature control have all been successfully employed. Conditioning agents include NH_3, NaCl, H_2SO_4, SO_3 and soluble sulfates.

Theoretically, corona discharge throughout the precipitator is continuous; practically, corona discharge emanates from a series of localized but mobile points on the discharge electrodes. Rectified alternating current is normally employed as the source of electrical energy and hence electrical field strength is not constant but varies continuously. High particulate concentrations increase the potential to produce corona and results in a reduction of current. These factors tend to result in a reduction of efficiency but are compensated for in the experimental determination of particle migration velocities.

Depending upon the size, shape, and packing characteristics of the dispersoid, the design velocity through a precipitator may range from 3 to 10 ft. per second. For any given set of conditions, the effect of increasing the velocity results in a reduction of retention time and in increased physical reentrainment of the deposited material. Generally, there is a critical gas velocity

for any specific dispersoid beyond which precipitation collection efficiency drops off rapidly. The problem of gas flow distribution in electrical precipitation is being given increased attention due to the relationship which has been shown to exist between precipitation-zone gas velocity and collection efficiency. The assumption that average gas velocity is representative of actual conditions may in many instances be entirely erroneous. Practically, if the gas velocity profile is decidedly irregular, the expected efficiency of the precipitator may not be attained. Several methods for equal flow distribution are presently employed. These include simple enlargement sections, baffles, directional vanes, and perforated plates. In some applications such devices have been used both upstream and downstream from the precipitation zone.

Electrical precipitators are the most efficient type of control equipment for dispersoids in common use today. Advantages possessed by this type of equipment are: 1) high collection efficiency for all ranges of particle size and for high grain loadings under severe operating conditions, 2) dry disposal of solid particulates if desired, 3) low maintenance and operating costs, 4) low pressure drop, and 5) large volume of high temperature gas can be satisfactorily handled. Disadvantages common to electrical precipitation include: 1) high initial cost, 2) large size of the equipment, and 3) possible explosion hazards.

For heavy duty operations, the disadvantage of high initial cost does not limit the application of precipitators, but for less demanding conditions, other high efficiency, less expensive, and less rugged equipment is normally employed. Collection efficiencies of 95% and higher are obtained with electrical precipitators in cases where particle sizes are as small as 0.01 microns and where operating conditions are extremely severe.

Scrubbers

In its most general sense the category of liquid scrubbers would include the various types of gas absorption equipment. As applicable, however, in the field of air pollution control the term "scrubber" usually is restricted to those devices which utilize a liquid to achieve or assist in the removal of solid or liquid dispersoids from the carrier gas stream. Generally, water is utilized as the scrubbing liquid although in special cases other liquids have been employed.

Scrubbers are constructed employing such a multiplicity of design that no single type is representative of the category as a whole. Some units consist simply of an existing dry-type collector modified by the introduction of a liquid phase to assist in particulate matter removal and to prevent reentrainment; other units are specifically designed to operate as wet collectors. In general, however, it may be said that dispersoids are collected in scrubbers by one or a combination of the following mechanisms: 1) impingement

of the dispersoid on the liquid medium, 2) diffusion of the dispersoid onto the liquid medium, 3) condensation of the liquid medium vapors on the dispersoid, thereby increasing its size and weight, and 4) partitioning of the gas into extremely small elements to allow collection of the dispersoid by Brownian diffusion and gravitational settling on the gas-liquid interface.

The objective of dispersoid-liquid contact sections in the several types of scrubbers is to present a large liquid surface area for the contact of the dispersoid in the carrier gas stream with the liquid phase. Both the mechanisms of impingement and diffusion are favored by high specific surface areas. Target efficiency for particles in the size range where Stokes' law applies is a function of the dimensionless group shown in the section on inertial separators. A general equation for impingement collection efficiency may be written[29,30]

$$E_s = 1 - e^{-(3E_t xy/2D_1)} \qquad (7)$$

where,

E_s = Weight collection efficiency, dimensionless

E_t = Target efficiency, dimensionless

x = Distance normal to gas flow through which collecting drop travels, cm or ft

y = Ratio of volumetric liquid rate to volumetric gas rate, dimensionless

D_1 = Diameter of collecting drop, cm or ft

Impingement type scrubbers, therefore, should operate more efficiently as the liquid droplet size is decreased. In consideration of the mechanism of impingement alone, however, it can be reasoned that because impingement efficiency depends upon relative velocity between dispersoid and liquid droplet, a minimum droplet size for optimum collection must exist. This is true because of the rapid acceleration to gas velocity undergone by very small droplets. It can be shown that impingement efficiencies fall off when collecting droplets smaller than 30-50 microns are employed.

In the extremely small dispersoid size range, the mechanism of diffusion becomes important in the collection of the dispersoids. Deposition on liquid droplets in the carrier gas stream will be effected by Brownian and eddy diffusion of the dispersoid. It is believed that the diffusion mechanism is predominant in the collection of sub-micron particles and may be sizable for dispersoids up to 5 microns in diameter. As in all diffusional processes the rate of diffusion is favored by large areas for diffusion, thereby making small liquid droplets with high surface-to-volume ratios a necessity for high collection efficiencies. In most practical applications the dispersoid to be removed is heterogeneous and both impingement and diffusion mechanisms operate.

The mechanism of condensation occurs when cooling, resulting from the liquid spray, causes the dispersoid-laden carrier gas to pass through its dew point. Condensation will then take place with the sub-micron particles acting as condensation nuclei,

thus increasing the effective size of the dispersoid. This mechanism is effective when initially hot gases containing relatively small dispersoid concentrations are conditioned.

Gas partitioning is achieved by dispersing the gas in very small increments through a liquid such that the distance between the suspended particles and the surrounding liquid-gas interface is extremely small. Separation of the dispersoid is then achieved by deposition on the gas-liquid interface by means of Brownian diffusion or gravitational settling. Effectiveness of this mechanism of separation increases with decreasing size of the gas increments.

The addition of surface-active agents to the liquid phase of scrubbers to enhance wetting characteristics is believed only to prevent reentrainment of the deposited dust particles and not to enhance materially the actual process of dust deposition. Sufficient data on this, however, are not available and further study will be required before definite conclusions as to the effectiveness of this approach can be determined.

A variety of designs have been employed as scrubbers. A general list of the basic types would include spray towers, jet scrubbers, venturi scrubbers, cyclonic scrubbers, inertial scrubbers, mechanical scrubbers, and packed scrubbers.

The spray tower is a common type in which the dispersoid-laden carrier gas passes through banks of sprays, directed either parallel or normal to the gas stream to achieve liquid contact with

the dispersoid. These sprays are followed by a set of staggered eliminator plates to remove the entrained water-dispersoid droplets. Water consumption varies from 1/2 to 2 gallons of water per thousand cubic feet of gas and pressure drops vary between 0.1 and 0.5 inch of water.

A modification of the spray tower is the water jet scrubber in which a high velocity jet of water is directed axially into the throat of a venturi section effecting intimate liquid contact with the dispersoid-laden gas. This type unit is normally followed by a simple gas reversal chamber to remove the entrained water-dispersoid droplets. Water consumption normally varies from 50 to 100 gallons per thousand cubic feet of gas and the jet is capable of developing pressure gains up to 8 inches of water.

A recent development employing the venturi principle is the venturi scrubber in which the dispersoid-laden gas stream is directed through the venturi with a throat velocity of from 200-300 ft. per second. Water sprays are introduced just preceding the venturi throat. The water and water-dispersoid droplets are then removed from the gas stream in a cyclonic spray separator. Water consumption varies from 3-10 gallons per thousand cubic feet of gas with a pressure drop across the entire unit of 10-15 inches of water.

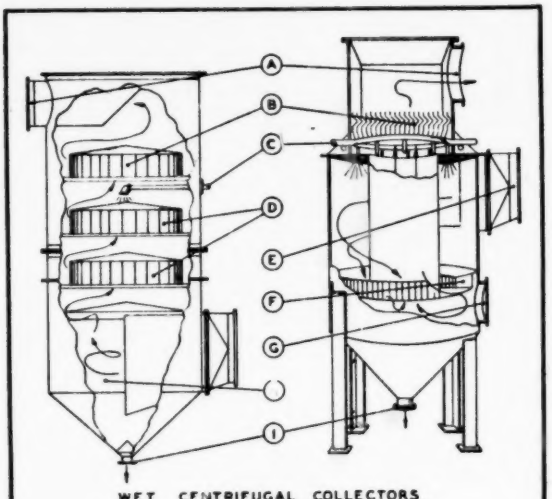
A modification of a type of dry collector by the addition of a liquid phase is the cyclonic scrubber. In this unit a series of radial sprays are introduced into a typical cyclone.

These sprays assist in the collection of the dispersoid and tend to prevent reentrainment. Pressure drops usually vary from 2-8 inches of water with water consumptions varying from 3-10 gallons per thousand cubic feet of gas.

Scrubbers in which liquid contact of the dispersoid is obtained as a result of the gas velocity itself are classified as inertial type scrubbers. Two fundamental types fall within this classification: first there is the impaction type scrubber in which the liquid phase and the dispersoid-laden gases are intimately mixed and are then impacted on a plate to promote additional dispersoid-liquid contact. Impaction velocities may range from 30-150 ft. per second with pressure drops up to 30 inches of water. Secondly, there is the deflection type scrubber which utilizes deflector plates to effect liquid-dispersoid contact and to assist in the dispersion of the spray droplets. Water consumption ranges from 6 to 10 gallons per thousand cubic feet of gas and pressure drops may be as high as 6 inches.

In mechanical scrubbers liquid-dispersoid contact is achieved by the simultaneous introduction of the liquid medium and the gas stream onto rotating disks, blades, or perforated plates. In some cases stationary members are alternated with the rotating elements. Generally, high collection efficiencies for small particle sizes require high power consumption.

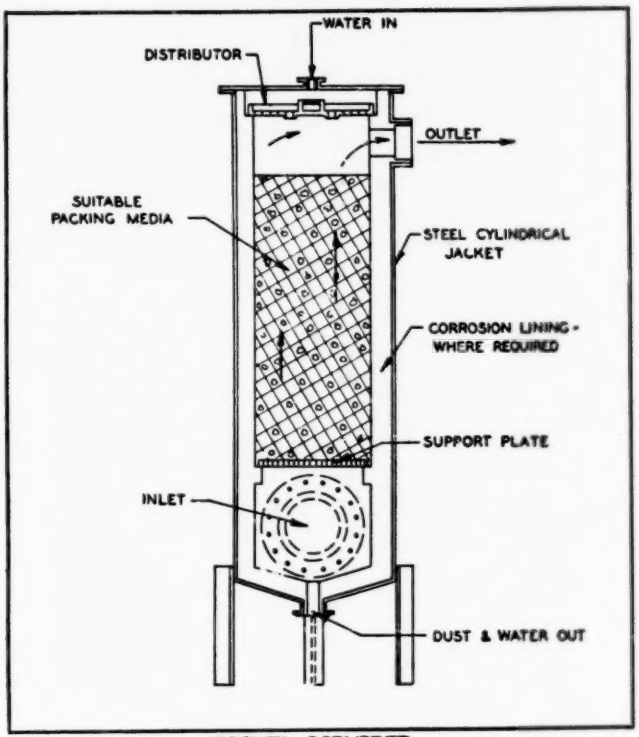
The final classification is the packed scrubber. This unit is simply a conventional packed tower employing Raschig rings,



MECHANICAL SCRUBBERS

Berl saddles, fiberglass, or other packing. Normally, gas flow is countercurrent to liquid flow in this type of equipment. The separating mechanism is believed to be primarily impingement of the dispersoid on the packing itself with the liquid medium merely acting to continually clean the surfaces of the packing material. Excessive superficial tower velocities tend to result in channeling through the packing material with a consequent reduction in efficiency. Pressure drops are on the order of 1/2 to 10 inches of water.

Regardless of the scrubbing mechanism involved, power consumption is the critical factor determining collection efficiency. Energy input is consumed either by high-pressure atomization of the liquid medium, high velocity jetting of the liquid medium, high velocity of the dispersoid-laden carrier gases, or by mechanical



PACKED SCRUBBER

impaction. Energy consumption in all cases will be approximately equal in attaining the same collection efficiencies. Simpler types of scrubbers with lower energy inputs are effective in collecting particles above 5-10 microns in diameter while the more efficient, high energy input scrubbers will perform efficiently for collection of particles as small as 1-2 microns in diameter.

Since the types of scrubbers available are so very diversified, the advantages and limitations of this classification of control equipment are difficult to generalize. It may be said, however, that this type of equipment has the following advantages: 1) moderately high collection efficiencies below 10 microns, 2) moderate initial cost, and 3) applicable for high temperature installations. Scrubbers are limited in their application,

however, in that they require: 1) wet disposal of the collected material, 2) variable power consumption, but high power consumption for higher efficiency, and 3) moderate to high maintenance costs due to corrosion and abrasion.

Control of Gaseous Contaminants

Control equipment for gaseous contaminants and odors must be considered apart from that for aerosols since the techniques employed differ basically. The control of noxious gases and odors is far from standardized due mainly to the widely varying chemical and physical properties and concentrations encountered. In addition, the importance attached to this type of contaminant is the result of a relatively recent trend in the air pollution field. Control equipment which has been used for gases and vapors includes combustion, absorption, and adsorption units.

Combustion is feasible where the pollutant gas or odorous components are oxidizable. Normally organic contaminants may be destroyed by exposure to temperatures in excess of 1200°F. Under certain conditions the use of catalysts may lower the required temperatures. The major limitation of this technique is that it may become too expensive when fuel values of the gaseous discharge are low, when moisture content of the discharge is high, or when exhaust volume is extremely large. Combustion type control equipment has been used advantageously, however, in the petrochemical, coffee roasting, paint and varnish, rendering, and

fertilizer industries. Fundamentally these combustion units must provide: 1) sufficient combustion air for the oxidation reaction, 2) adequate temperature for continuous oxidation of the gaseous contaminant, and 3) adequate retention time in the high temperature combustion zone for completion of the oxidation reaction. Generally the incineration equipment consists of a single combustion chamber with provisions for maintaining continuous and intimate mixing of the contaminant-laden gas and the flame from the auxiliary burner. The combustion chamber is proportioned such that the gas velocity and gas flow patterns established will produce adequate retention time in the combustion zone. Average retention time in such units is 0.2 to 0.3 seconds at temperatures of 1200°F. and higher.

Absorption involves the transfer of gas molecules into a liquid phase. It is a diffusional process and, as such, the driving force consists of concentration differentials between the bulk gas phase and the gas-liquid interface and between the interface and the bulk liquid. The various resistances to mass transfer should be as low as possible and the absorption process is, therefore, favored by high interfacial surface areas, turbulence in both fluid phases, and high diffusion coefficients. An absorbent is normally selected which has a high capacity to absorb without build-up of appreciable back pressures. To achieve this, the gas to be absorbed should have a high solubility in the chosen absorbent or the gas should react irreversibly with the absorbing liquid.

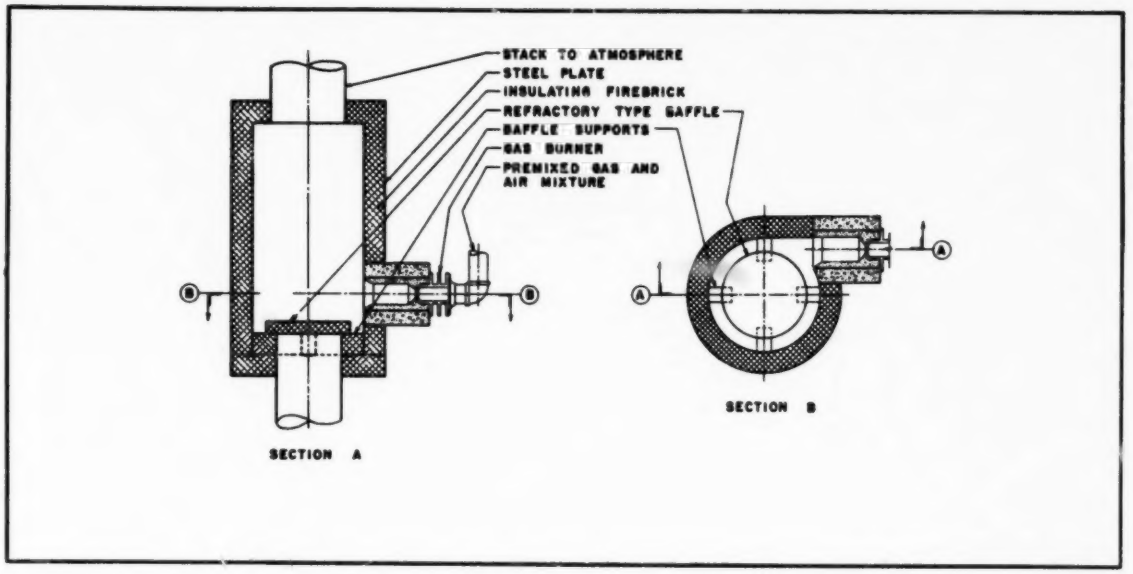


DIAGRAM OF A
WASTE GAS AND ODOR INCINERATOR

Normally in industrial absorption operations the concentration of the solute gas in the carrier gas is relatively high. This may not be true where the control of air pollution is the objective. Very large gas volumes containing only low concentrations of pollutants are often handled and the equipment required may be quite large relative to that employed in chemical processing. In addition, the carrier gas may contain particulate matter requiring that the gas absorption equipment also function as a wet dust collector.

In general, absorption equipment may be classified as spray chambers, mechanical contactors, bubble cap or sieve plate contactors, or packed towers. A spray chamber, as the name implies, is simply an empty chamber in which the gas stream is

passed through curtains of liquid spray. Mechanical contactors employ mechanical agitation to accomplish intimate contact of gas and liquid. In a bubble cap or sieve plate contactor, the gas is passed upward through a series of plates on which pools of absorbent exist; bubble cap trays are used in the former and porous or perforated plates in the latter to support the liquid layers. Packed towers allow the liquid absorbent to flow by gravity downward through a bed of packing material while the gas stream moves either concurrently or countercurrently through the tower. In each of the above units, intimate gas-liquid contact is promoted over large interfacial areas.

The above types of contactors have certain relative advantages and disadvantages. Spray chambers have low pressure drops and will not plug; they also will function as simple spray type dust collectors. In addition, these chambers have been found to be fairly effective in the removal of even rather insoluble gases and may, therefore, compare favorably with other types of equipment in certain applications.[31,32] Mechanical contactors are, of course, more complex in construction and higher in cost. They are quite useful, however, when the gas to be absorbed is relatively insoluble and liquid diffusion resistance is controlling. Packed towers may plug with solids and cleaning is not easy. Consequently, grid packings rather than dumped packings are often used to overcome plugging tendencies and to lessen pressure drop.

Plate towers will normally operate at higher pressure drops than packed towers but they may be much more easily cleaned and may be more effectively used as combination absorber dust collectors.

Adsorption is another diffusional process which is growing in importance as a separation mechanism. Adsorption is a surface phenomenon and requires the presence of large solid surface areas to be effective. In almost all cases these areas are internal as with porous material and may be almost unbelievably great per unit of adsorber volume. Adsorption may be primarily physical in nature or may include chemical surface reaction as in chemisorption.

Although adsorption has been used very successfully in certain industries for many years, the theory and techniques involved are not nearly so well known as those for distillation, filtration, extraction, etc. This is particularly true when it is applied in a new field such as air pollution control. While considerable experimental work has been done to enable prediction of flow patterns, pressure drops, material balances, and transport and adsorption rates, there is not complete agreement on the various design procedures proposed. In actual practice the adsorptive capacity, height of bed, and stripping conditions for a given adsorption problem, in most cases, are obtained experimentally as a basis for design of full-scale equipment.

It appears that adsorption as a means of air pollution control may offer certain advantages for some classes of

contaminants. These classifications include gases or vapors for which other means of collection are uneconomical, hazardous, or impossible. For example, many flammable organic compounds may be recovered with relatively high efficiency by adsorption at concentrations safely below the lower explosive limits of the compound. Also, since adsorption may give very complete clean-up even when pollutant concentrations are very low, unusually toxic or odorous compounds may sometimes be removed by adsorption on activated carbon, etc. when all other practical methods fail.

Adsorption equipment is almost always the packed bed, although fluidized beds can also be used. Power consumption is dependent on the height of the adsorbing bed, the adsorber pellet size, and the flow rate, and pressure drops may vary from a few inches of water upward.

The generation of heat of adsorption in a bed may make necessary pre-cooling of the effluent gas in some cases. It must be noted that normally both adsorptive capacities and collection efficiencies fall off with higher temperatures. Installation costs for adsorbers are high but maintenance and operating costs are not excessive. Small sized units will operate as efficiently as larger ones and many times the value of the recovered material will enhance economic feasibility.

THE APPLICATION OF PROCESS CHANGES FOR THE PREVENTION OF AIR POLLUTION

In controlling air pollution by process changes, the method to be employed is completely dependent upon the particular process involved; hence, no fixed set of rules can be universally applied. Selection of the control method must be based on: 1) a determination of the types of contaminants creating an air pollution problem, 2) a complete evaluation of the plant processes to ascertain the units or operational areas discharging the offending contaminants, and 3) determination of specific adequate control techniques for those contaminants.

Four basic approaches to the control of contaminants through process modification are available: 1) substitution of raw materials or fuels, 2) modification of the process itself, 3) modification or replacement of process equipment, or 4) changes in operational practices.

The substitution of raw materials or fuel has often been used successfully as a method of atmospheric pollution control when the contaminant being eliminated from the fuel or raw material is not essential to the process. For example, bauxite flux may be substituted for fluorspar in open hearth practice and powdered sulfur has been replaced as a flux in the manufacture of magnesium castings. Both changes result in decreased emission of air pollutants. Also, the use of low-volatile coals in place of high-volatile coals has proved most effective in eliminating smoke and

soot in many commercial and industrial heating applications and the substitution of low-sulfur fuels for high-sulfur fuels has reduced the SO_2 discharges quite appreciably.

In modifying a given process to effect a reduction in atmospheric pollution, a unit operation may be eliminated or modified, or other unit operations may be substituted or added. Elimination of atmospheric pollution caused by the manufacture of intermediate raw materials can be achieved by acquiring such components through purchase from an outside supplier; thus, the manufacturing process creating air pollution can be discontinued. The addition of an operational step to reduce atmospheric pollution has been successful in brass foundry practice in which indirect fired furnaces are employed. A fluxing material is applied to the surface of the molten brass serving as an evaporation barrier and reducing the emission of brass fumes; this additional step is included strictly as an air pollution control measure. Also, the control of pollution by substituting one complete operation for another is illustrated in the disposal of combustible refuse where incineration may be discontinued in favor of sanitary land fill.

Changes in equipment as a method of reducing the release of contaminants to the atmosphere may include 1) the modification of one or more items of basic process equipment, 2) the substitution of one type of equipment for another type, or 3) the replacement or repair of faulty or malfunctioning equipment. An illustration of this is the use of vapor recovery systems to control

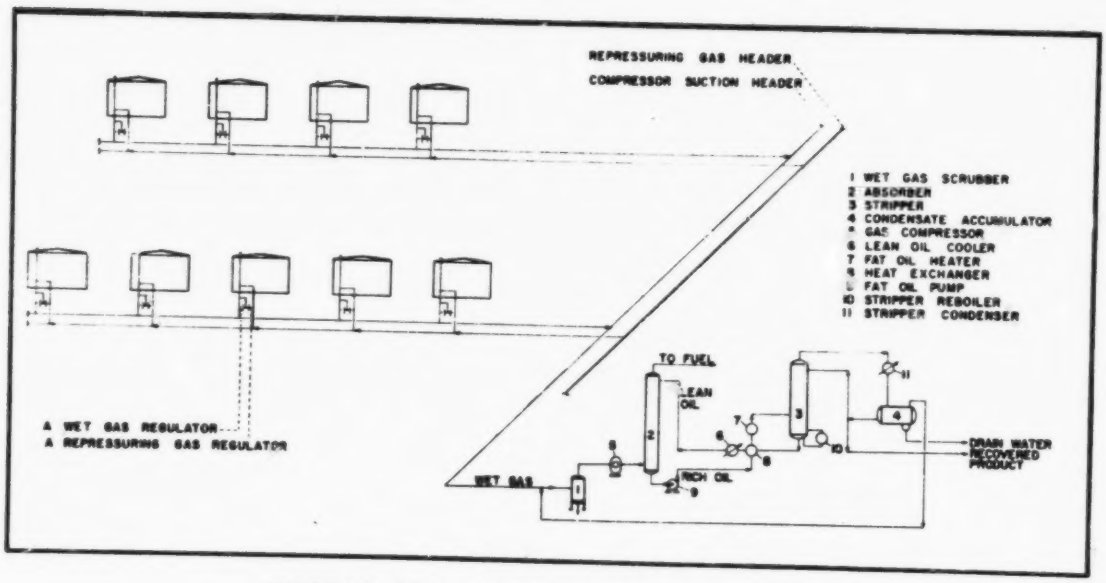
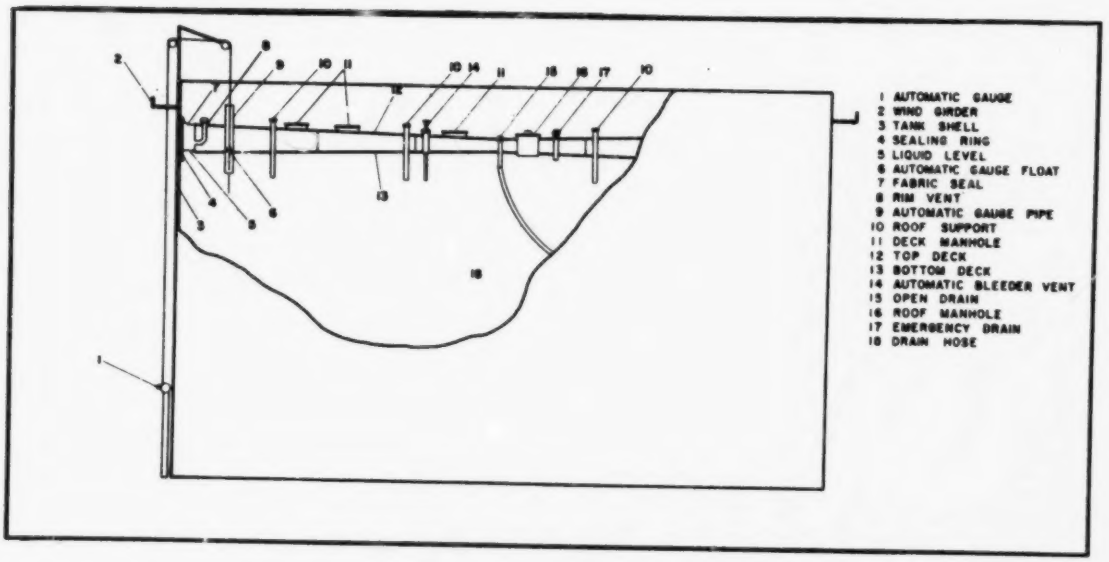


DIAGRAM OF A VAPOR RECOVERY SYSTEM

vapor losses in the handling of volatile materials. Headers, compressors, absorbers, and condensers may be employed to return effluxing vapors to the system. The installation of sealed storage tanks, e.g., floating roof tanks, is another example. In the cast iron foundry industry the substitution of reverberatory furnaces for cupolas has proven successful in reducing the contaminant discharge from this type of operation.

Changes of operational procedures for the sole purpose of reducing pollution discharge is well illustrated by the technique practiced in power plant operation by the Tennessee Valley Authority. Here the rate of release of sulfurous emissions from coal burning operations is reduced during periods of adverse meteorological conditions by firing a low-sulfur fuel in place of the normal



DOUBLE DECK FLOATING ROOF TANK

high-sulfur fuel. It is also common to reduce atmospheric contamination from boiler operation by employing recommended procedures for starting and cleaning fires and by using accepted stoking techniques, etc.

An important example of air pollution control by process changes lies in combustible waste disposal. This process will, therefore, be discussed in detail to illustrate the type of research which can be conducted for determining proper design and operational changes to reduce the emission of air pollutants.

Incineration of Combustible Wastes

A significant factor affecting the concentration of pollutants within the air mass of any specific area is the contaminant

discharge produced from the disposal of combustible wastes by incineration. Other methods of disposal of such wastes include open dumping, sanitary land fill, and composting, none of which, when properly operated, create any appreciable air pollution problem. However, the selection of a particular method of waste disposal must be based on such factors as the combustible content of the refuse, economic considerations relating to the various methods of disposal, and upon sanitary and aesthetic requirements of the area.

Disposal of combustible wastes by incineration has the distinct advantage over other methods of reducing the volume of refuse by as much as 95%, leaving a residue with little or no organic material. Such residues, therefore, require a minimum land usage for disposal and the disposal area is not subject to excessive settling after compaction.

Incineration is defined as any combustion process employed for the disposal of combustible wastes such as refuse, rubbish, garbage, human and animal remains, and solid, semi-solid, liquid, and gaseous waste products. To be effective from the air pollution standpoint, incineration must achieve: 1) maximum combustion efficiency in order to reduce atmospheric discharge of smoke, tars, malodorous compounds and other products of incomplete combustion, and 2) maximum retention of the incombustible solids in order to minimize fly ash and other solid discharges to the atmosphere.

Although engineering parameters are available for the design of industrial process furnaces burning fuels of uniform composition at specified rates, such data are not available for the design of incinerators. This results from the fact that incinerators are frequently batch fired and are required to perform satisfactorily over wide ranges of operating conditions while burning high volatile fuels. Further, incinerators are normally charged at varying rates with heterogeneous materials of varying composition, and with corresponding variations in combustion air flow rate and air distribution. This results in widely fluctuating combustion chamber temperatures. Unless the incinerator is able to accommodate these wide ranges in operating characteristics, excessive atmospheric contaminants will be discharged.

Incinerators may be classified broadly as to the number of combustion stages employed in the process, i.e., single-stage or multiple-stage. Single chamber incineration equipment is constructed such that drying of the fuel, gasification and combustion of the volatile components of the fuel, and ignition and combustion of the fixed carbon proceed in a single stage. Combustion air is supplied both underfire and overfire, and mixing of the overfire air with the volatilized gases, necessary for good combustion, is comparatively poor due to the configuration of the chamber and, of more import, to lack of facilities to expedite proper mixing.

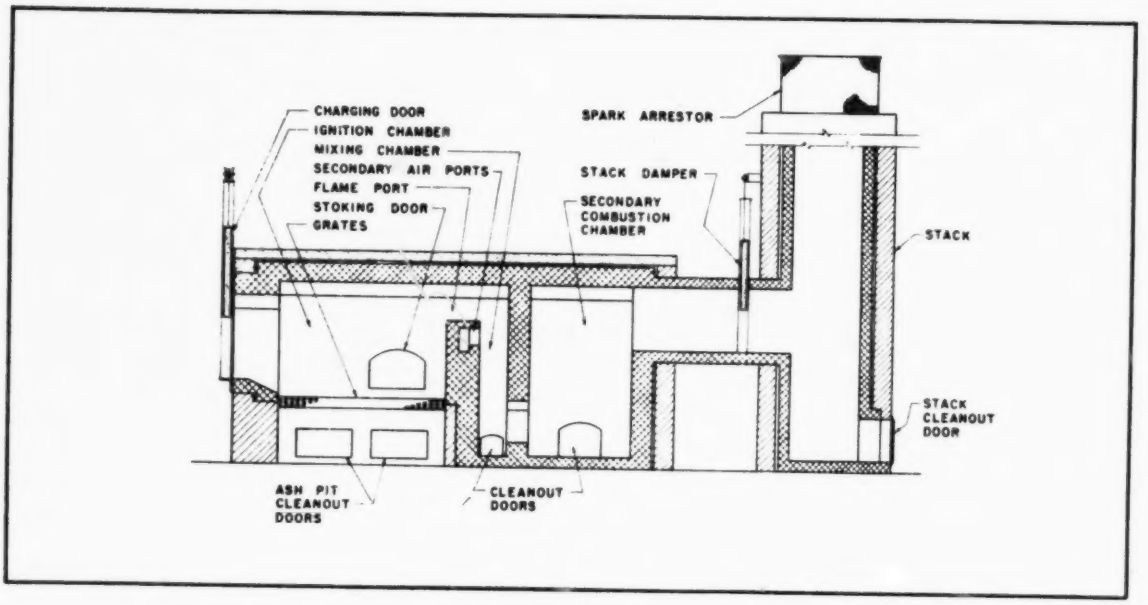


DIAGRAM OF A
LARGE MULTIPLE CHAMBER INCINERATOR

Additional research to improve combustion efficiency in single chamber incinerators is at present under way and preliminary results indicate that considerable improvement in this type of incineration equipment may be achieved.[33] Tangential air jets are employed to improve mixing of the volatile unburned constituents of the fuel with combustion air. Burning rate and amount of excess combustion air have been indicated to be functions of both mass flow rate of air and Reynolds number of flow through the ports. Optimum conditions in a prototype experimental unit were obtained employing an average excess air of approximately 40%. The height of the port above the fuel bed has also been shown to affect combustion efficiency and burning rate. Although these effects were not marked, in general, combustion efficiency was

greatest with higher ports and burning rate highest with low ports close to the fuel bed surface.

Proper designs for multiple chamber incineration processes require that the equipment be constructed such as to promote a two-stage combustion mechanism. Drying of the fuel, ignition and combustion of the fixed carbon, and gasification and partial combustion of the volatile components proceed in the ignition chamber or primary stage. The gas phase combustion reaction is completed in the second stage which consists of both a mixing chamber and a combustion chamber. Secondary air is admitted at the entrance to the mixing chamber to assist the completion of the gas phase combustion reaction.

Three fundamental design concepts for multiple chamber incineration processes affect the combustion efficiency. These concepts are: 1) ratio of grate loading to combustion rate, 2) combustion air distribution, and 3) ignition chamber proportions.

Present data indicate that burning rates of from 40-50 pounds per sq. ft. of grate area per hour are optimum. It should be noted that these rates are applicable only for the large municipal type incineration equipment, above 50 tons per day capacity. For smaller capacity incinerators grate loading expressed in pounds per sq. ft. of grate area per hour decreases as a logarithmic function of combustion rate expressed in pounds-per-unit time.[34]

$$G_L = 16.5 + 9 \log C_R \quad \text{(special units)} \qquad (8)$$

where, G_L = optimum grate loading, $(lb)/(ft^2)(hr)$

C_R = combustion rate, lb/min

The second concept fundamental to incinerator design when considered from the air pollution standpoint relates to combustion air distribution. Of significance in this respect is the ratio of underfire air (combustion air distributed through the grate) to overfire air. Present data indicate that optimum results are obtained when 65 to 75% of the actual combustion air requirements for the incineration process, based on 100% excess air, are supplied overfire. The ratio must, however, be based upon stoichiometric air requirements for the particular chemical composition of the fuel concerned.

The third concept concerns ignition chamber proportions. In the past these have been considered to be related to ignition chamber volume. It has been found that a refinement of this concept exists in the relationship of arch height to grate area. While this relationship does establish the ignition chamber volume, it has been indicated to be more definitive in establishing combustion rate and contaminant discharge than direct volumetric relationships. An empirical formula for this relationship has been developed.[35]

$$A_H = \frac{6}{5} G_a^{0.364} \quad \text{(special units)} \qquad (9)$$

where, A_H = arch height, ft

G_a = grate area, ft^2

Relatively little data are available on solid and gaseous discharge from incineration processes. Available data[36] indicate that commercial or industrial single chamber incinerators with no adequate provisions for controlling combustion air, discharge an average of 20 pounds of solid contaminants to the atmosphere per ton of material burned. Further, an average of 24 pounds of solids are discharged to the atmosphere for each ton of material consumed in a "backyard" type incinerator and 19 pounds for every ton burned in a "chute fed" apartment house type incinerator. Municipal incinerators of the multiple chamber type employing secondary air and with provisions for combustion air control produce an average of 8.8 pounds of solids per ton of material burned with a range from 3.4 to 17.8 pounds per ton. Unpublished data on industrial and commercial multiple chamber incinerators, with capacities up to 4,000 pounds per hour, indicate an average loss of solid contaminants to the atmosphere of 6.8 pounds per ton of material burned with a range of 3.0 to 14.7 pounds per ton.

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